Nuclear structure studies of microsecond isomers near A = 100

J. Genevey, J.A. Pinston, G.S. Simpson, W. Urban

Nuclear Structure studies of Microsecond Isomers near A = 100

J. GENEVEY, J.A. PINSTON, G. SIMPSON

Laboratoire de Physique Subatomique et de Cosmologie,
IN2P3-CNRS/Grenoble Universités, F-38026 Grenoble Cedex, France
** E-mail: genevey@lpsc.in2p3.fr*

W. URBAN

Faculty of Physics, Warsaw University,
ul. Hoża 69, 00-681 Warsaw, Poland

A large variety of shapes may be observed in Sr and Zr nuclei of the $A = 100$ region when the number of neutrons increases from $N = 58$ to $N = 64$. The lighter isotopes are rather spherical. It is also well established that three shapes co-exist in the transitional odd-A, $N = 59$, Sr and Zr nuclei. For $N > 59$, strongly deformed axially symmetric bands are observed. Recently, a new isomer of half-life 1.4(2) μs was observed in ^{95}Kr, the odd-odd ^{96}Rb has been reinvestigated and a new high spin isomer observed in the even-even ^{98}Zr. Beyond $N = 60$ nuclei, the neutron-rich Mo isotopes represent well deformed nuclei, but at the same time, the triaxial degree of freedom plays an important role. We have re-investigated the odd ^{105}Mo and ^{107}Mo and found that odd and even Mo in the neutron range N = 62-66 have comparable quadrupole and triaxial deformation. These nuclei were studied by means of prompt γ-ray spectroscopy of the spontaneous fission of ^{248}Cm using the EUROGAM 2 Ge array and/or measurements of μs isomers produced by fission of ^{239,241}Pu with thermal neutrons at the ILL (Grenoble).

Keywords: Exotic nuclei, Shape coexistence

1. INTRODUCTION

The region of neutron-rich nuclei near $A = 100$ is distinctive for its sudden change in the ground state properties of nuclei [1]. In particular, for the even $_{38}$Sr and $_{40}$Zr isotopes a sudden onset of strong deformation is observed at $N = 60$, whereas the lighter isotopes up to $N = 58$ are rather spherical. The isotones with $N = 59$ neutrons are of special interest because they are just at the border of the two regions.

Previous experiments have shown that their ground and low-lying states

are rather spherical [2,3], while deformed bands with $\beta_2 \sim 0.3$ are present at about 600 keV excitation energy [1] and the maximum deformation of the region, $\beta_2 \sim 0.4$, is reached for the $9/2^+[404]$ band recently observed at 829.8 and 1038.8 keV, in ^{97}Sr and ^{99}Zr respectively [4–6]. The large β_2 value found for this band is observed for several even and odd Sr and Zr nuclei above $N = 60$. A simple explanation of the shape-coexistence mechanism has been proposed. It is based upon the Nilsson diagram and stresses the fundamental importance of the unique parity states [7,8]. Beyond $N = 60$ nuclei, the neutron-rich Mo isotopes represent well deformed nuclei, but at the same time, the triaxial degree of freedom plays an important role.
This paper summarizes the results obtained in this field by our group. After the description of the experimental techniques in section 1, we will present our recents results in the $N = 58$-60 region (Section 2) and in the $N = 62$-66 region (Section 3).

2. Experimental techniques

The Lohengrin mass spectrometer was used to select nuclei, according to their mass-to-ionic charge ratios (A/q), recoiling from a thin ^{239or241}Pu target which was undergoing thermal-neutron-induced fission. The flight time of the nuclei through the spectrometer was around 1.6 μs. The fission fragments (FFs) were detected in an ionization chamber filled with isobutane gas. Two different setups have been installed at the focal plane of the spectrometer.
In the first setup, the FFs were detected in a gas detector of 13 cm length, and subsequently stopped in a 12 μm thin Mylar foil. Behind the foil, two cooled adjacent Si(Li) detectors covering an area 2×6 cm^2 were placed to detect the conversion electrons and X-rays, while the γ-rays were detected by two Ge of 60 % placed perpendicular to the beam. This setup allows conversion electrons to be detected down to low energy (15 keV) and allows γ-electron coincidences to be obtained. Details on this experimental setup can be found in [9,10].
In the second setup, the FFs were detected in an ionization chamber filled with isobutane at a pressure of 47 mb. This ionization chamber has good nuclear charge (Z) identification. It consists of two regions of gas, $\Delta E1$=9 cm and $\Delta E2$=6 cm, separated by a grid. This system is able to identify the nuclear charge in the Z∼40 region, with a resolution ($FWHM$) of about two units. The γ rays deexciting the isomeric states were detected by a Clover Ge detector and three single Ge crystals of the Miniball array [11] assembled in the same cryostat. All these detectors were placed perpendic-

ular to the ion beam. They were packed in a very close geometry, thanks to the small thickness (6 cm) of the ionization chamber. The total efficiency for the γ detection is 20 % and 4 % for photons of 100 keV and 1 MeV respectively. Any γ rays detected in the germanium detectors up to 40 μs after the arrival of an ion were recorded on the disk of the data acquisition system. A time window of 250 ns was used for γ-γ coincidences in the data-analysis software.

3. The N = 58-60 isotopes

3.1. ^{95}Kr

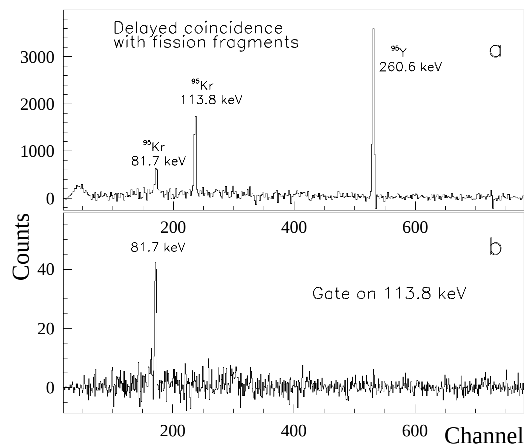

Fig. 1. (a) γ decay spectrum of the ^{95}Kr and ^{95}Y isomers. (b) coincidence spectrum gated on the 113.8 keV γ ray.

Two μs isomers have been observed in the $A = 95$ mass chain. The strong γ line of 260.6 keV in Fig. 1a deexcites an isomeric level of 56.2 μs half life, already assigned to ^{95}Y [12]. The two weaker γ-rays of 81.7(2) and 113.8(2) keV energies belong to a new isomer [13]. As seen in Fig. 1b, the two transitions are in coincidence with each other. This new isomer has a half life of 1.4(2) μs.

The method used for the nuclear charge (Z) identification of this new isomer of mass 95, is shown in Fig. 2. The ^{95}Y isomer was already known and its

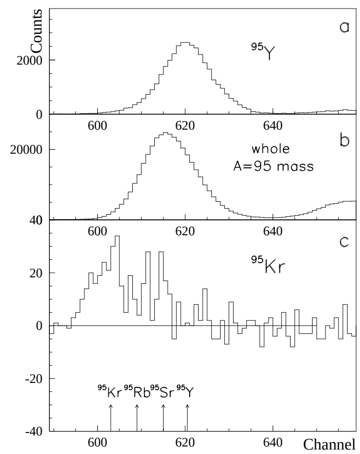

Fig. 2. Energy lost in the first step of gas Δ E1, for (a) the ^{95}Y isomer, (b) the whole $A = 95$ mass chain, and (c), the ^{95}Kr isomer.

$\Delta E1$ is shown in Fig. 2a. The $\Delta E1$ spectrum for the whole mass chain 95 is shown in Fig. 2b. The $\Delta E1$ spectrum of the new isomer is shown in Fig. 2c. It was obtained by coincidences between the incoming ions and the γ-rays of the isomer. The position of the centroid of the $\Delta E1$ distribution allows the nuclear charge $Z = 38$ to be assigned to this new isomer unambiguously. More details on the method can be found in Ref. [13].
In Fig. 3, the level scheme of the new isomer found in ^{95}Kr is shown and compared with the previously known isomers in the isotones of ^{97}Sr and ^{99}Zr [2–5,14]. In these three nuclei, the low-lying isomer decays by an $E2$ transition. The measured $B(E2)$ values, 1.33(5), 1.75(10) and 1.47(27) $Wu.$, for ^{99}Zr, ^{97}Sr and ^{95}Kr, respectively, are comparable, which suggests that the three transitions have an analogous nature and that the three isotones have the same spins. The ground and the two first excited states of these three isotones are very likely spherical, as suggested by the measured $B(E2)$ values, and their dominant configurations are the $\nu s_{1/2}$, $\nu d_{3/2}$ and $\nu g_{7/2}$ shell-model states, respectively. One may notice that their energies change very little between ^{99}Zr, which is quite close to the line of stability and ^{95}Kr, which is very far from it.
In contrast, we have not observed the $9/2^{+}[404]$ strongly deformed isomer, present in the two other isotones [4]. The non observation of this isomer means that either this level does not exist in ^{95}Kr, it is too weakly fed by

fission, or its half life is shorter than about 0.5 μs, because the flight time throw the Lohengrin spectrometer is about 1.7 μs.

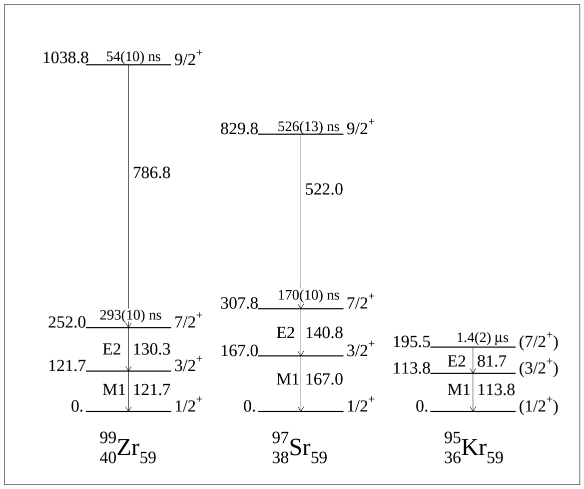

Fig. 3. Decay schemes of the ^{99}Zr, ^{97}Sr, and ^{95}Kr isomers.

3.2. ^{96}*Rb*

The N=59 odd-odd very neutron-rich ^{96}Rb nucleus has been reinvestigated [15]. It was previously measured by Genevey *et al.* [16] with the Lohengrin spectrometer at the ILL reactor in Grenoble. The γ-counting rates obtained in this new measurement are about ten times higher than in the previous one. Examples of $\gamma-\gamma$ coincidences are reported in Fig. 4. The level scheme based on $\gamma-\gamma$ and $e-\gamma$ coincidences is shown in Fig. 5.
This scheme is very similar to the one observed in ^{98}Y [17]. The low-lying levels are rather spherical as well as well as the 10^- isomeric state. The two rotational bands are fed by μs isomers close in excitation energy, 1181.5 keV in ^{98}Y and 1135 keV in ^{96}Rb, and the isomeric transitions have comparable $B(E2)$ values. All these features, strongly suggest that the two isomers have the same $(\pi(g_{9/2})\nu(h_{11/2}))_{10^-}$ configuration. A strongly attractive $n-p$ interaction explains the presence of these isomers at a relatively low energy. Consequently, the strong n-p interaction may induce a competition between high-spin, fully-aligned spherical configurations and the levels of rotational bands in this transitional region. Moreover, it is interesting to note that

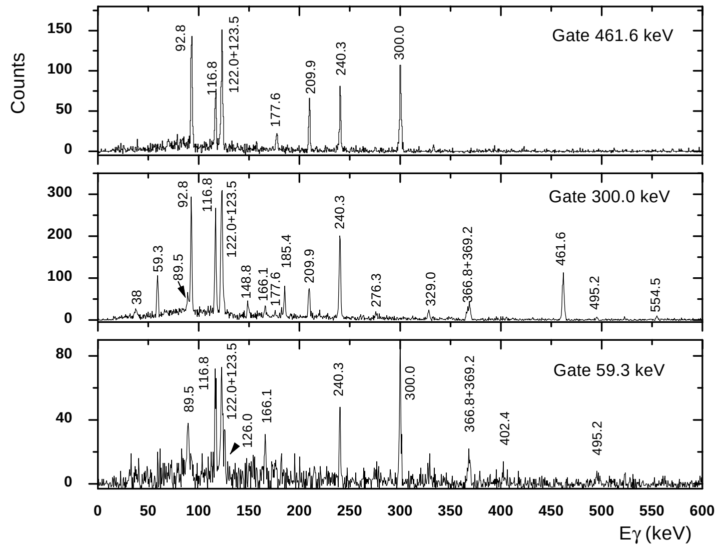

Fig. 4. Examples of $\gamma - \gamma$ coincidences in ^{96}Rb.

the neutron and proton orbitals present in the configuration of the spherical isomer and in the deformed band of these odd-odd nuclei originate together from the same spherical unique-parity states $\pi(g_{9/2})$ and $\nu(h_{11/2})$.

3.3. ^{98}Zr

A new (17^-) μs isomeric state at 6603.3 keV has been observed for the first time in ^{98}Zr [19]. Mass and isotopic identification of the isomer were performed by examining coincidences between the mass-separated ions, detected in the ionization chamber, and the isomer-delayed γ rays. Much of the decay scheme below the isomer has already been assigned to ^{98}Zr. This nucleus has previously been studied by prompt γ-ray spectroscopy of secondary fission fragments populated by light-ion induced [6] and spontaneous fission [1,20]. The proposed level scheme is presented in figure 6.

This new 1.9 (2) μs isomer at 6603.3 keV observed in ^{98}Zr, with a proposed configuration of $\pi(g^2_{9/2})\nu(g^1_{7/2}h^1_{11/2})$ and a single particle nature, decays by a pure, or almost pure, $E2$ transition into a 15^- state, which then decays into two collective bands, one of positive parity, the other negative, the latter of which is observed for the first time. The existence of a spherical, single-

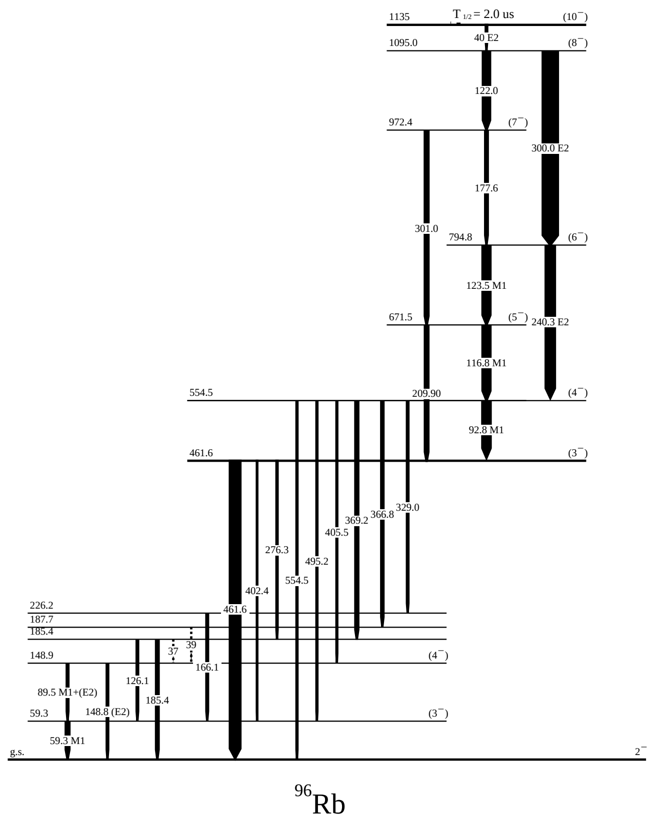

Fig. 5. Decay scheme of the 2.0 μs isomer in ^{96}Rb obtained in the present work. The low-lying levels and the isomer at 1135 keV have rather spherical configurations, while a rotational band develops above 460 keV.

particle state at such a high energy (6603.3 keV) and spin (17^-) is quite unusual, in fact both these values are the highest known for a μs isomer in this region. These high-spin shape coexisting states again demonstrate the richness of nuclear structure phenomena in this region.

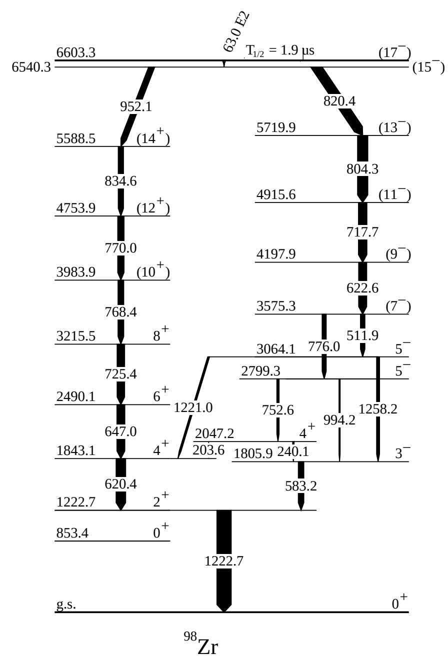

Fig. 6. Decay scheme of the 1.9 (2) μs isomer observed in the present work. The 853.4 keV 0^+ bandhead [1] is also included.

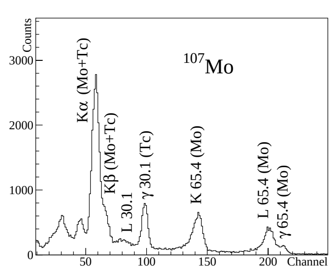

Fig. 7. Si(Li) spectrum of the A=107 isomers observed in the present experiment. Narrow peaks correspond to X- and γ-rays, while the broader peaks are due to conversion electrons.

4. The N=62-66 region : ^{105}Mo and ^{107}Mo

In the even-even $^{104-108}$Mo a new situation occurs [21–23]. These nuclei are strongly deformed ($\beta_2 \approx 0.37$) but at the same time, the levels of

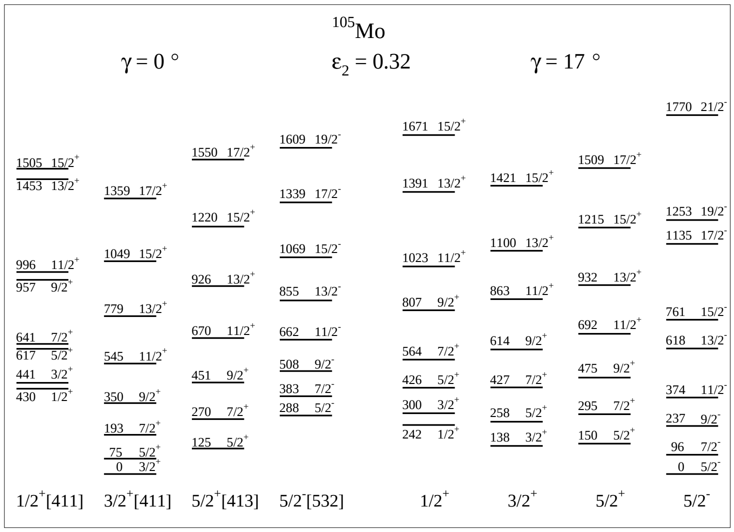

Fig. 8. Calculated levels for the four bands in ^{105}Mo performed for γ deformations 0° and 17°, respectively. It is worth noting that the staggering in the $1/2^+$ and $5/2^-$ differs strongly for these two deformations.

the $K^\pi = 2^+$ γ-band go down in energy with the increase of the neutron number, suggesting that the triaxial degree of freedom plays an important role in these isotopes. The ^{105}Mo nucleus was populated in spontaneous fission of ^{248}Cm and prompt γ-rays following fission were measured using the EUROGAM2 array. Four well developed bands were observed in ^{105}Mo [24]. In ^{107}Mo, three well developed bands were previously reported from γ-ray measurements of the spontaneous fission of ^{248}Cm [25]. To complete the level scheme, this nucleus has been produced through thermal-neutron induced fission reaction of a ^{241}Pu target, at the ILL reactor in Grenoble. Figure 7 shows the Si(Li) spectrum of the A=107 isomers observed in this experiment. A new isomer of 420 ns half live has been observed in this work. It has been tentatively assigned as a $1/2^+$ state deexciting by an $E2$ transition to the $5/2^+$ ground state. This wealth of information in ^{105}Mo and ^{107}Mo, which is unique in the neutron-rich odd Mo isotopes, makes a comparison in the frame of the rotational model meaningful [24].
The excited states of the bands in ^{105,107}Mo and their γ-ray decay patterns were calculated using the code ASYRMO [26]. Figure 8 gives the results of the calculation for the lowest four bands in ^{105}Mo and Figure 9 for ^{107}Mo. A satisfactory fit to the experimental data has been obtained using the simple

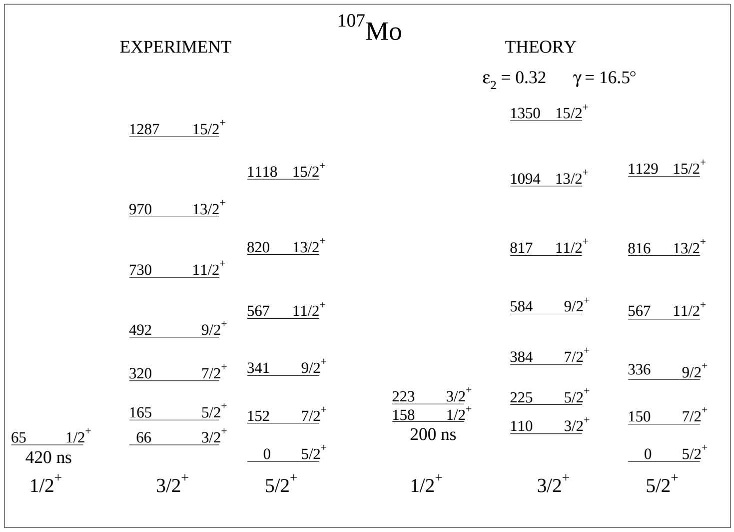

Fig. 9. Comparison of the experimental levels of the three positive parity bands in ^{107}Mo with theory.

particle-rotor calculations for both ^{105,107}Mo assuming that these nuclei are asymmetric rotors with remarkably similar deformations, $\epsilon_2 = 0.32$ and $\gamma \approx 17°$. It is worth noting that four bands of the same origin observed in these two nuclei are well reproduced by these parameters. For the even-even $^{104-108}$Mo, the parameters of γ and quadrupole deformation can be deduced from the experimental data. These values are comparable to the ones observed in the odd Mo. Moreover, a comparable triaxial deformation ($\epsilon_2 \approx 0.32, \gamma \approx 22°$) was also reported for ^{107}Tc, with $N = 64$ neutrons [27]. All these data strongly suggest that the cores have similar shapes in the heavy even-even and odd-neutron Mo nuclei, as well as in the odd-proton Tc nuclei, and that the odd-A nuclei are not strongly affected by the unpaired particle.

5. Conclusion

In Table 1 are reported the nuclear shapes observed in the $A \sim 100$ region. A great wealth of information was recently gained in the odd-mass and odd-odd N=59 isotones. It is now well established that three shapes coexist in ^{97}Sr and ^{99}Zr, while two different shapes were seen in ^{96}Rb. The two

Table 1. Nuclear shapes in the A $\sim$ 100 region

Nuclei	A	Z	N	β_2	γ
Kr	95	36	59	<0.20 ; ?	0
Rb	96	37	59	<0.20; 0.28-0.39	0
Sr	97	38	59	<0.20; 0.32; 0.41	0
Zr	99	40	59	<0.15; 0.30; 0.41	0
Sr	98	38	60	0.40	0
Zr	98	40	60	0.40	0
Mo	104-108	42	62-66	0.38	~20°
Mo	105-107	42	63-65	0.38	~17°
Tc	107	43	64	0.38	~22°

unique-parity states $\pi(g_{9/2})$ and $\nu(h_{11/2})$ play a considerable role in all these nuclei. The relative occupation of these orbitals is able to change drastically the shape of the nucleus.

For $N = 60$ Sr and Zr nuclei the β_2 deformation is at the maximum value of the region. For even and odd Mo isotopes, the triaxial degree of freedom becomes important. A satisfactory fit to the experimental data has been obtained for both ^{105}Mo and ^{107}Mo in simple particle-rotor calculations, assuming that these nuclei are asymmetric rotors. The parameters of the model are very similar for both nuclei. It is important to note, that in both nuclei all four bands are well reproduced using the same γ parameters. Moreover, in the neutron range N=62-66, the γ deformation of the odd Mo are very close to the values of the even-even Mo, suggesting that all these nuclei have comparable core deformations.

References

1. W. Urban, J.L. Durell, A.G. Smith, W.R. Phillips, M.A. Jones, B.J. Varley, T. Rząca-Urban, I. Ahmad, L.R. Morss, M. Bentaleb, N. Schulz Nucl. Phys. **A689**, 605 (2001)
2. K.L. Kratz *et al.*, Z. Phys. A, **312**, 43 (1983).
3. L.K. Peker, Nucl. Data Sheets **73**, 1 (1994).
4. W. Urban, J.A. Pinston, J. Genevey, T. Rząca-Urban, A. Złomaniec G. Simpson, J.L. Durell, W.R. Phillips, A.G. Smith, B.J. Varley, I. Ahmad, and N. Schulz, Eur. Phys. J. A**22**, 241 (2004).
5. J.K. Hwang *et al.*, Phys. Rev. C **67**, 054304 (2003).
6. C.Y. Wu, H. Hua, D. Cline, A.B. Hayes, R. Teng, R.M. Clark, P. Fallon, A. Goergen, A.O. Macchiavelli, K. Vetter. Phys. Rev. C **70**, 064312 (2004).
7. J.A. Pinston, J. Genevey, G. Simpson, W. Urban in *3rd Internatinal Workshop on Nuclear Fission and Fission-product Spectoscopy* (AIP conference proceedings 798 p.149, 2005)
8. J.A. Pinston, Science and Technology Journal, Bulgarian Nuclear Society

ISSN1310-8727 P. 48, 2005.
9. J.A. Pinston, and J. Genevey, J. Phys. J. G **30**, R57 (2004).
10. J. Genevey, J.A. Pinston, H. Faust, C. Foin, S. Oberstedt, and M. Rejmund, Eur. Phys. J. A **9**, 191 (2000).
11. J. Eberth *et al.*, Rep. of Progr. in Nucl. Phys. 46, 389 (2001).
12. B. Pfeiffer, E. Monnand, J. A. Pinston, F. Schussler, G. Jung, J. Munzel and H. Wolnik, Proc. Int. Conf. Far from Stability, Helsingor, Denmark 7-13 June 1981, CERN report 81-09, p. 423.
13. J. Genevey, R. Guglielmini, R. Orlandi, J.A. Pinston, A. Scherillo, G. Simpson, I. Tsekhanovich, N. Warr, J. Jolie Phys. Rev. C **73**, 037308 (2006).
14. A. Zlomamaniec, H. Faust, J. Genevey, J.A. Pinston, T. Rząca-Urban, G.S. Simpson, I. Tsekhanovich and W. Urban, Phys. Rev. C **72**, 067302 (2005).
15. J. A. Pinston, J. Genevey, R. Orlandi, A. Scherillo, G.S. Simpson, I.Tsekhanovich, W.Urban, H.Faust, N.Warr. Phys. Rev. C **71**, 064327 (2005).
16. J. Genevey, F. Ibrahim, J.A. Pinston, H. Faust, T. Friedrichs, M. Gross, and S. Oberstedt, Phys. Rev. C **59**, 82 (1999).
17. S. Brant, G. Lhersonneau, and K. Sistemich, Phys. Rev. C **69**, 034327 (2003).
18. C. Thibault *et al.*, Phys. Rev. C **23**, 2720 (1980).
19. G.S. Simpson, J.A. Pinston, D. Balabanski, J. Genevey, G. Georgiev, J. Jolie, D.S. TJudson, R. Orlandi, A. Scherillo, I.Tsekhanovich, W. Urban, N. Warr. Phys. Rev. C . To be published
20. J.H. Hamilton, A.V. Ramaya, S.J. Zhu, G.M. Ter-Akopian, Y.T.Oganessian, J.D. Cole, J.O. Rasmussen, M.A. Stoyer Prog.Part.Nucl.Phys. **35**, 635 (2001).
21. A. G. Smith, J.L. Durell, W.R. Phillips, M.A. Jones, M. Leddy, W. Urban, B.J. Varley, I. Ahmad, L.R. Morss, M. Bentaleb, A. Guessous, E. Lubkiewicz, N. Schulz, and R. Wyss, Phys. Rev. Lett. **77**, 1711 (1996).
22. A. Guessous, N. Schulz, M. Bentaleb, E. Lubkiewicz, J.L. Durell, C.J. Pearson, W.R. Phillips, J.A. Shannon, W. Urban, B.J. Varley, I. Ahmad, C.J. Lister, Morss, K.L. Nash, C.W. Williams, and S. Khazrouni, Phys. Rev. C **53**, 1191 (1996).
23. H. Hua, C. Y. Wu, D. Cline, A. B. Hayes, R. Teng, R. M. Clark, P. Fallon, A. Goergen, A. O. Machiavelli, and K. Vetter, Phys. Rev. C **69**, 014317 (2004).
24. J.A. Pinston, W. Urban, Ch. Droste, J. Genevey, T. Rzaca-Urban, G. Simpson, J.L. Durell, A. G. Smith, B.J. Varley, I. Ahmad. Phys. Rev. C . To be published
25. W. Urban, T. Rzaca-Urban, J. A. Pinston, J. L. Durell, W. R. Phillips, A. G. Smith, B. J. Varley, I. Ahmad, and N. Schultz, Phys. Rev. C **72**, 027302 (2005).
26. P. Semmes and I. Ragnarsson, *The Particle plus Triaxial Model: a User's Guide, distributed at the Hands-on Nuclear Physics Workshop, Oak Ridge, 5-16 August 1991 (unpublished).*
27. Y. X. Luo *et al.*, Phys. Rev. C**70**, 044310 (2004).